Evaluation of the RBM10 Water Quality Model
for Developing a Temperature Total maximum Daily Load
for the Columbia and Snakes Rivers

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Introduction

RBM 10 is a one dimensional water quality model that simulates water temperature using traditional thermal energy budget methods and gradually varied hydraulics. Kalman filtering is used to account for uncertainty in the water temperature data used to develop the model. Models of this type have been used to assess water temperature in the Columbia River system for a number of important environmental analyses. The Federal Water Pollution Control Administration developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River Thermal Effects Study (Yearsley, 1969). The Bonneville Power Administration and others used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the Columbia River System Operation Review (BPA, 1994). Normandeau Associates used a one-dimensional model to assess temperature conditions in the Lower Snake River for the US Army Corps of Engineers (USACE, 2000).

RBM 10 simulates average temperature for the cross sectional area of the river for selected time steps. We have used it to simulate daily and hourly average temperatures for the cross sectional area of the river at discreet points along the longitudinal axis of the river.

The numerical water quality criteria for the Idaho, Washington and the Colville Confederated Tribes are expressed as daily maximum temperatures: instantaneous values. The numerical water quality criteria for Oregon are expressed as the seven day moving average of the daily maximum temperature and if there is insufficient data to establish a seven day average of daily maximum temperatures, the numerical criterion is applied as an instantaneous maximum. Since the model results are averages for the cross sectional area of the stream and time step, they do not relate exactly to the water quality standards.

In evaluating the appropriate model for use in developing this TMDL we looked at the purpose of modeling in development of the TMDL, the quantity and quality of information needed to develop a valid model, the availability of that information and the cost versus the benefits of the model. It is important to choose a model that can perform the desired analysis but it is also important to choose a model that can be supported by the information that is available. Depending on the information available it is sometimes necessary to choose between estimating statistical averages with considerable demonstrated accuracy or estimating specific values with less accuracy or little means to evaluate the accuracy. We selected a model that simulates average temperature conditions rather than a multidimensional model because:

- it will achieve the purposes of the modeling exercise to simulate temperature conditions in the absence of the human activities;
- sufficient information is available to accurately simulate average conditions but not to

accurately simulate instantaneous conditions; and

- the value added from simulating instantaneous conditions does not merit the costs in this case.

Purpose of the model is to simulate temperature conditions in the absence of the human activities that currently exist

The water quality standards for most of the subject river reaches prohibit exceedance of temperature criteria as a result of human activities (Washington WQS) or anthropogenic activities (Oregon WQS). This requires an estimate of what temperature conditions would be in the absence of the human activities that currently exist. The purpose of the modeling is to simulate temperature conditions in the absence of the human activities. The question we are answering is "What effect has human activity had on the temperature regime of the Columbia and Snake Rivers?" The real challenge to this effort is that the river system without human activity that we are simulating no longer exists, so we can not collect the data from it that is needed to build and operate the model, nor can we compare model results to observations from the river to verify the accuracy of the model. So we selected a modeling strategy with this limitation in mind.

In answering the question, "What effect has human activity had on the temperature regime of the Columbia and Snake Rivers?", we have framed a solution that will provide an accurate and reliable estimation of the effect of human activity. We are focusing on the effects of human activity on the overall temperature regime, not instantaneous, localized effects that are gone when the river water mixes. We are focussing on those effects that persist in the river and therefore change the temperature regime. That is to say, affects that warm the river or shift the annual temperature patterns of the river. To estimate whether particular human activities have effected the temperature regime we have chosen to simulate the daily and hourly, cross sectional average temperature. We can simulate these parameters more accurately with the data that is available than we can simulate instantaneous values for any location in the river. A comparison of simulated average temperatures for the river with the major human activities removed to current average temperatures with those activities in place will provide a pragmatic estimation of the effects of human activities on water temperature that can be used to establish the TMDL.

The data needed to simulate average temperatures is available while the data needed to simulate instantaneous values is not available and would be very costly in terms of time and money to collect.

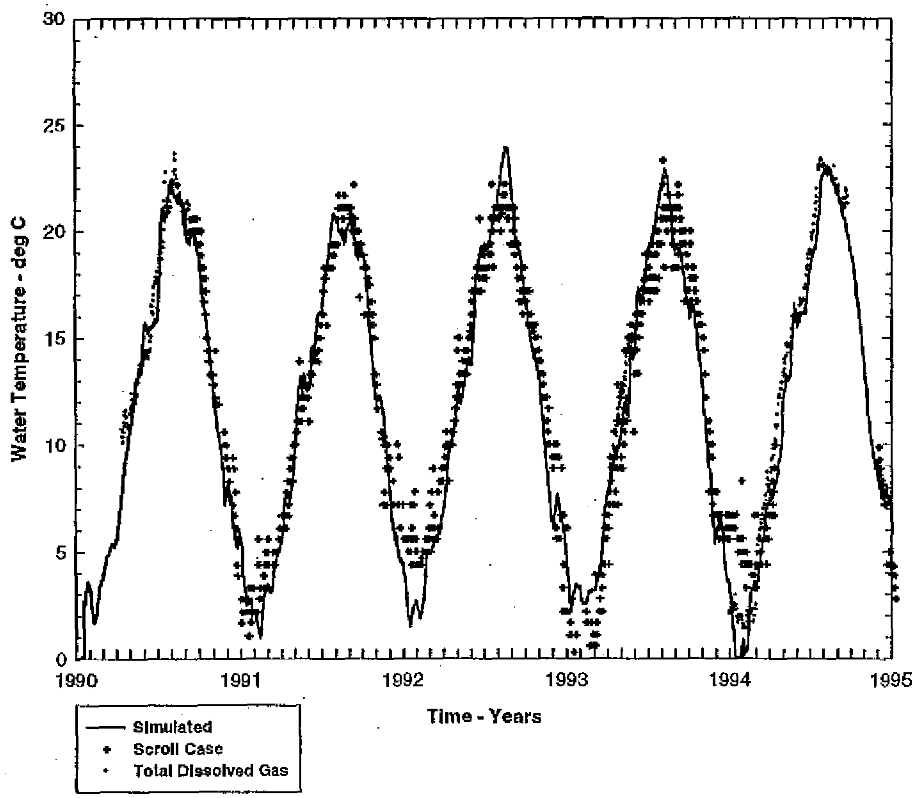
We can simulate the average temperature more accurately because we do not have to account for the infinite variations in meteorology, channel width, depth and slope, shoreline shape, current and many other parameters. These variations along the river have a greater effect on instantaneous temperatures in specific locations than they do on the average temperature of the river. We could simulate the instantaneous temperature to some degree if we had the data from the river and the river basin necessary to explain meteorology, channel configuration, etc.

specifically enough to support such a simulation. But since the river is no longer available for such measurements and the basin is so large, we have somewhat limited information for both historic conditions and current conditions. For example, there are only four first-order meteorological stations in the basin, located in Lewiston, ID, Pendleton, OR, Spokane, WA and Yakima, WA. Further, information is lacking on the initial stream temperatures entering the modeled area so estimation techniques were used for those initial inputs. These types of limitations on the available information have less effect on simulations of average temperature than on simulations of instantaneous temperature.

This is not to say that we do not have a lot of information for modeling the river systems. We do have a great deal of good specific information from a number of locations that we are applying generally to over 900 river miles. The information is sufficient to do a good job of estimating average river temperatures along the longitudinal axis of the rivers. The ability of RBM10 to simulate average temperature is depicted in Figures 6 - 14 and Appendix D of the Modeling Assessment (Yearsley, 2001). The figures are attached as Appendix A. They visually demonstrate the accuracy of the model in simulating known water temperatures. Figure 1, below is an example. It compares the simulated and observed water temperatures from John Day Dam.

Figure 1: Simulated and observed water temperatures at John Day Dam.

Figure 9. Simulated and observed water temperatures at John Day Dam for the period 1990-1994.



Appendix D of the modeling assessment report is a statistical analysis of the simulation results. It is attached as appendix B. The analysis for the same data shown in Figure 1 is included in Table 1 below.

Table 1. Mean and standard deviation of the difference between observed and simulated temperatures at John Day Dam (Columbia River Mile 215.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	0.580	1.309
March-April	1.273	0.730
May-June	0.283	0.924
July-August	0.288	0.986
September-October	0.9425	0.646
November-December	---	---
Entire Year	0.560	1.021

Table 2, taken from the Statistical analysis demonstrates the overall correlation between simulated and observed values.

Table 2. Slope of line and R^2 for regression of observed temperature data on simulated results in the Columbia and Snake rivers for the period 1990-1994. Regression was constrained to force the straight line to pass through the origin (X (simulated)=0, Y (observed)=0).

Measurement Site	Slope of Line	R^2
Wells Dam	0.995	0.973
Priest Rapids Dam	0.999	0.940
McNary Dam	1.004	0.929
John Day Dam	0.995	0.976
Bonnevile Dam	0.995	0.904
Lower Granite Dam	1.005	0.931
Little Goose Dam	0.997	0.907
Lower Monumental Dam	0.992	0.923
Ice Harbor Dam	0.998	0.929

Based on the evaluation of the simulation results, summarized here and presented in detail in Appendices A and B we are confident in the model's ability to simulate average temperature under existing river conditions. We can not do the same comparison for simulations of average temperature in the absence of human activities but based on the results with existing conditions we believe that the model can accurately simulate average temperature in the absence of human activities. This will give us a good answer to the question, "What effect has human activity had on the temperature regime of the Columbia and Snake Rivers?"

A model capable of simulating instantaneous values anywhere in the river would have to be a multi-dimensional, hydrodynamic model. That is, a model that simulates temperature along three axes: longitudinal, horizontal and vertical; simulates a dynamic, ever changing flow regime; and accounts for dispersion or diffusion. Such models have been developed and are frequently used for modeling rivers for which the extensive data requirements of such a model can be met. However, we are modeling over 900 miles of stream length and 259,000 square miles of watershed. The amount of information needed to support a multidimensional model of this magnitude is not available and would be very resource intensive to collect. The Corps of Engineers Waterways Experiment Station developed a proposal to use the CEQual2e model to simulate temperature in the Columbia/Snake mainstems. They derived a cost of $1.7 million (Personal Communication, 3/01). Further the data collection would require a number of years. We believe that the added value derived from such a modeling effort to TMDL development does not justify the huge costs.

The value added from simulating instantaneous conditions does not merit the costs in this case.

The value provided by the RBM10 model is a set of reliable and pragmatic measures of the impacts of human activity on the overall temperature regime of the rivers. We will be able to simulate the impacts on daily, cross sectional average temperature and hourly cross sectional average temperature. We will use that to estimate the maximum cross sectional average temperature each day, to illustrate the responses of temperature to changing meteorology and to illustrate diurnal fluctuations of temperature. The reliability of the RBM10 simulations is demonstrated in Appendices A and B.

The daily and hourly, cross sectional average temperature for the existing river system can be estimated readily from temperature data collected from TDG monitoring stations in the tail races of all the dams. Readings are taken hourly at these stations and the water in the tail race is well mixed from the reservoir above, minimizing the effects of any vertical or horizontal gradients that may have existed. The measurements represent a cross sectional average temperature for each hour and the daily average can be computed from the hourly measurements. So sampling sites are available with historic information on the daily and hourly cross sectional average temperature and there is a commitment to continue this sampling program into the foreseeable future. Furthermore, the hourly, cross sectional averages can be used as an estimate of instantaneous values if it is deemed necessary to relate the averages to instantaneous temperature for the TMDL.

The cross sectional average temperature is a pragmatic target because it provides a measure of the impacts of human activity on the whole river system. Changes in average temperature provide a clear signal of impacts important enough to be addressed by management actions and that can be readily measured in the field to monitor effectiveness of management actions and to allow iterative management should those steps prove to be inadequate. Further, the cross sectional average temperature is pragmatic because it provides information at a level of detail that we can use to derive TMDL numerical targets. This won't be a simple task.

The WQS for temperature in the Colville Reservation, Oregon and Washington have temperature criteria that are related to natural temperature conditions whenever natural conditions exceed certain specified threshold temperatures. The threshold temperatures vary with river reach. Essentially the criteria prohibit exceedance of the thresholds due to "human activities" (Colville Reservation and Washington) or "anthropogenic activities" (Oregon).

In reaches of the river where natural stream temperatures exceed the numerical thresholds, the simulations of natural temperature in the river are going to be used to establish the target temperatures for the TMDL in the Colville Reservation, Oregon and Washington. Since the WQS prohibit temperatures above numerical criteria *due to human activities*, the TMDL target temperature varies as the natural temperature varies. Of course the natural temperatures can vary in four dimensions: length, width and depth of the river and time. It would be very difficult to develop a target temperature regime for the TMDL in all of those dimensions. The cross sectional average temperatures will allow development of target temperatures in two dimensions: length of the river and time.

The added value of a multidimensional model would be to provide more information on the temperature regime in the reservoirs where vertical temperature gradients or even temperature stratification can be established. In such situations high temperatures may develop in the surface waters. Two dimensional modeling would be particularly appropriate in the storage reservoirs that develop durable thermal stratification. There is only one storage reservoir in the modeling area, Lake Roosevelt, and a 2 dimensional model will be used there if possible. The thermal gradients that develop in the run-of-the-river reservoirs are generally weak or the result of cool water releases from upstream. For example Karr, et al reported temperature gradients in the four lower Snake River reservoirs ranging from no gradient to 4 degrees Centigrade near Ice Harbor Dam on August 8, 1991 before cool water releases from Dworshak dam started (Karr etal, 1998). There was about a 1 degree Centigrade gradient in Lower Granite Reservoir (Karr etal, 1998). On August 23, 1991, when Dworshak was releasing 10,000 cfs of water at 7.2 degrees Centigrade, the thermal gradient in the lower 3 reservoirs ranged from no gradient to about 1.5 degrees Centigrade, but in Lower Granite reservoir the gradient was over 6 degrees Centigrade. The cool water release appears to have created the gradient in Lower Granite and broken down the gradient near Ice Harbor.

It is apparent that the TMDL will have to consider the temperature gradients that can develop in the reservoirs. But modeling those gradients with a multidimensional model will be greatly complicated by operation of the hydro system as discussed above and by the limitations on available information. A great deal of uncertainty will exist around the simulations and given the size and number of reservoirs it will be almost impossible to verify the simulations with the confidence that we have for the cross sectional averages. So we would be making policy decisions with more specific information but with little idea of how much uncertainty surrounds that information. Rather than model thes temperature gradients, a level of detail which introduces greater uncertainty, we believe it is more prudent to relate existing information on observed gradients to simulations of average temperature and make more confident decisions on how the TMDL should address the temperature gradients. There are a number of limnological studies like the one summarized above that describe the gradients that can develop under different conditions of flow released by the hydro system. Also there are TDG monitoring stations in the fore bays of the dam that measure temperature at 15 to 20 feet deep. These data provide information on the temperature of the surface waters that can be applied to the RBM 10 simulations to incorporate the gradients into the TMDL.

So the primary benefits of multidimensional modeling would be enhanced understanding of the temperature regimes of the reservoirs. But there will be a great deal of uncertainty associated with simulations of the reservoir temperature regimes. Futher, we believe that existing temperature data from limnological studies and TDG monitoring stations in the forebays of the reservoirs can be used in conjunction with RBM10 simulations to develop the TMDL. The costs of multidimensional modeling will be high monetarily (est about $1.7 million) and in terms of time. Therefore, given the uncertainties in the multi-dimensional modeling and the availability of good information to describe surface temperatures in the reservoir, we do not believe that the benefits of the multidimensional modeling justify the costs.

Temperature gradients in the reservoirs are an example of localized impacts on temperature that might be important to salmon and are not captured in the RBM10 model. There are two other types of localized temperature effects that are or may be important to salmon and won't be captured by the model. The first is fish ladders. The water in the fish ladders can be quite warm and possibly deter migration through the ladder. The model won't discern the water temperatures in the fish ladders, but it doesn't need to. The TMDL will establish the same target temperatures to be met in fish ladders as in the rest of the river reach they are in. The other example of localized effects can occur at NPDES discharges. The model will identify those that raise the average temperature of the river, but some that do not alter the average temperature may have plumes of elevated temperature that won't be shown by the model. Again, the model doesn't really need to discern these plumes. The TMDL will establish the same target temperatures for these dischargers as for the rest of the river reach they are in. If a greater level of detail regarding the effects of certain point sources is needed, they could be modeled individually.

Summary and Conclusions

The model selected for use in development of the Columbia/Snake River TMDL must be able to reliably estimate the effects of human activity on the temperature regimes of the two rivers. The daily and hourly, cross sectional average temperatures simulated by the RBM10 model are reliable statistics upon which to estimate the effects of human activity on the temperature regime. Sufficient information about the existing river, the river in the absence of human activities, meteorology in the basin and other factors exist to reliably simulate cross sectional average temperature. This is demonstrated by comparisons of simulations of the existing river to daily averages estimated from actual temperature data collected from the spill ways of the dams. The daily, cross sectional average temperature could actually be used as a surrogate for the daily maximum water quality standard as allowed in the TMDL regulations because it would be a somewhat conservative surrogate. However, sufficient information exists to relate the averages to daily maxima, so either option can be selected in developing the TMDL. Models that can predict the instantaneous maximum temperatures along the river at different depths and at different locations across the river are available. However, they require a great deal more data. Much of the required data is not available. The primary benefit of these models would be to provide information on the temperature regimes of the reservoirs that develop temperature gradients. We believe that there will be too much uncertainty associated with these simulations and that we can more reliably use existing information to factor the temperature gradients into the TMDL.

References Cited

Yearsley, J. 1999. Columbia River Temperature Assessment: Simulation Methods. United States Environmental Protection Agency, Region 10, Seattle, WA.

Appendix A: Simulated and Observed Water Temperatures at Locations on the Columbia and Snake Rivers (From Yearsley, 1999).

Figure 6. Simulated and observed water temperatures at Wells Dam for the period 1990-1994.

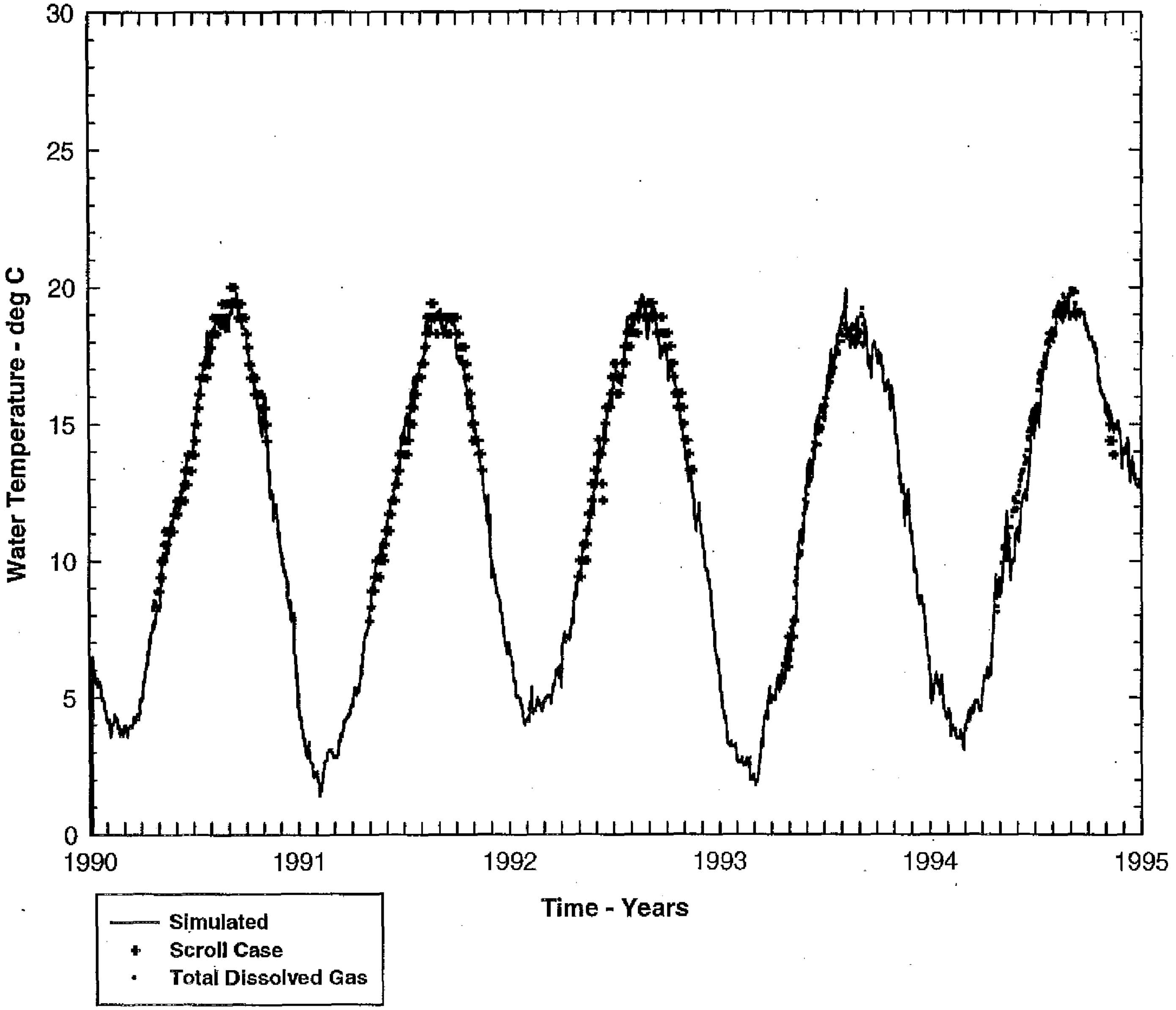


Figure 7. Simulated and observed water temperatures at Priest Rapids Dam for the period 1990-1994.

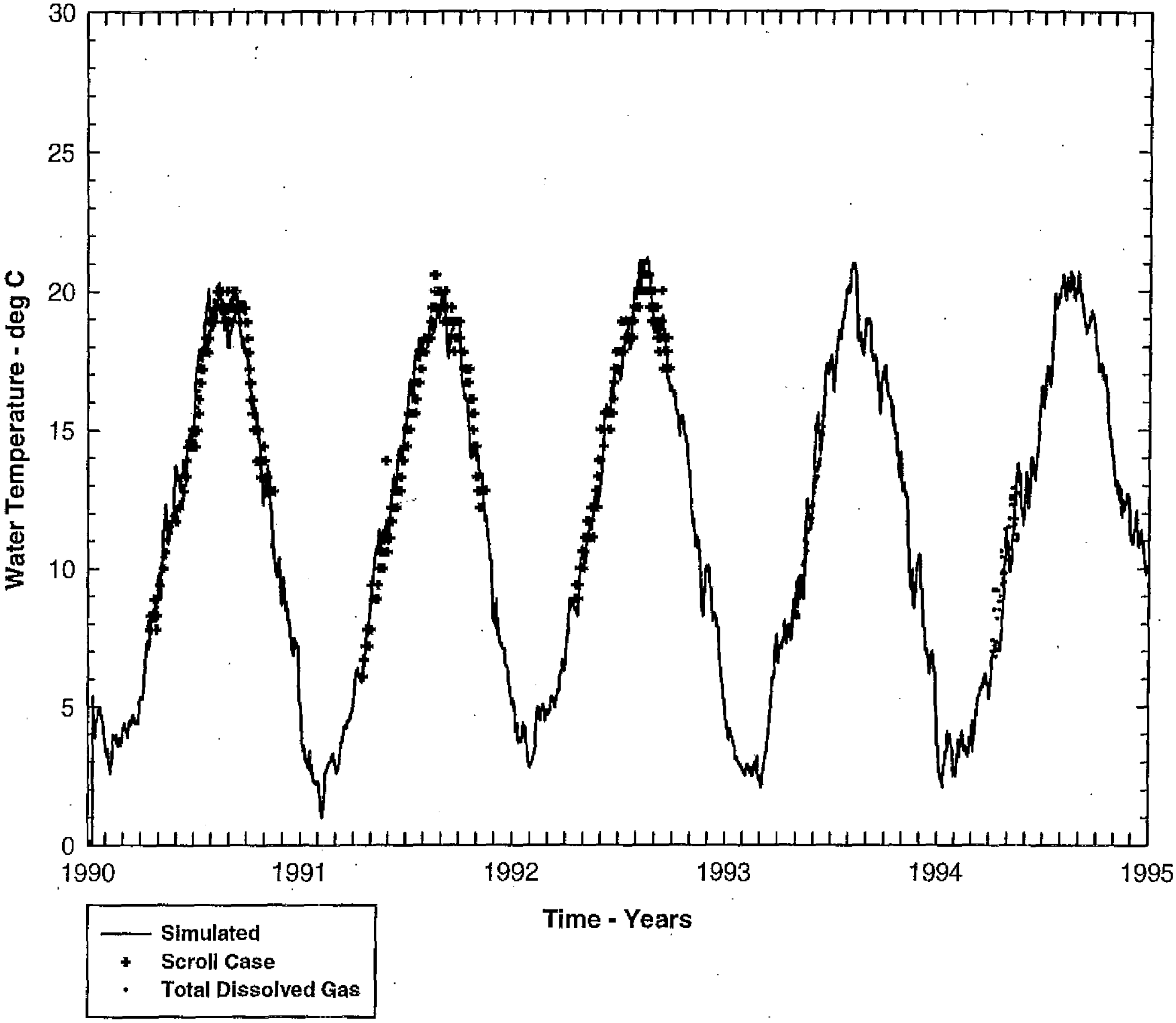


Figure 8. Simulated and observed water temperatures at McNary Dam for the period 1990-1994.

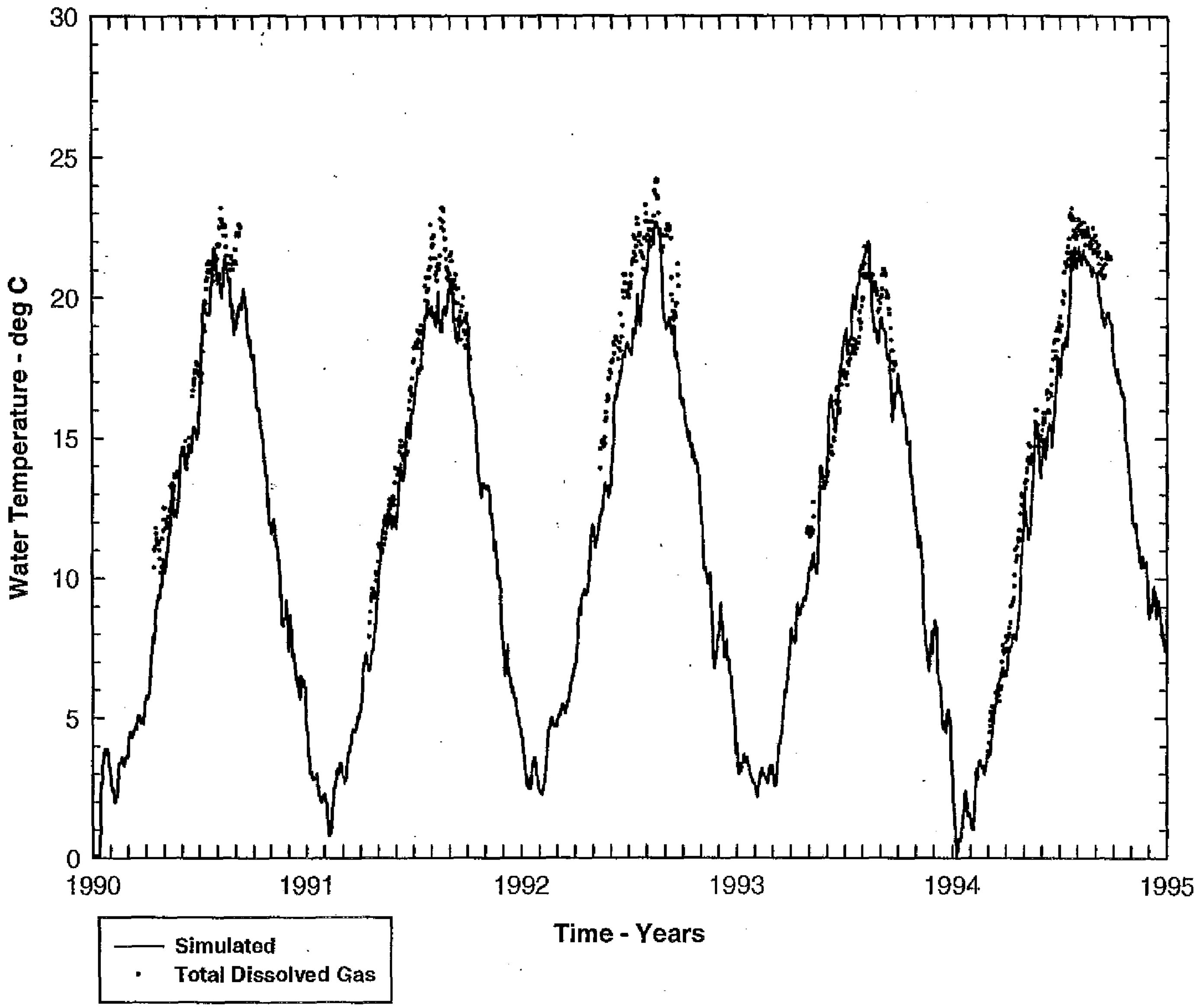


Figure 9. Simulated and observed water temperatures at John Day Dam for the period 1990-1994.

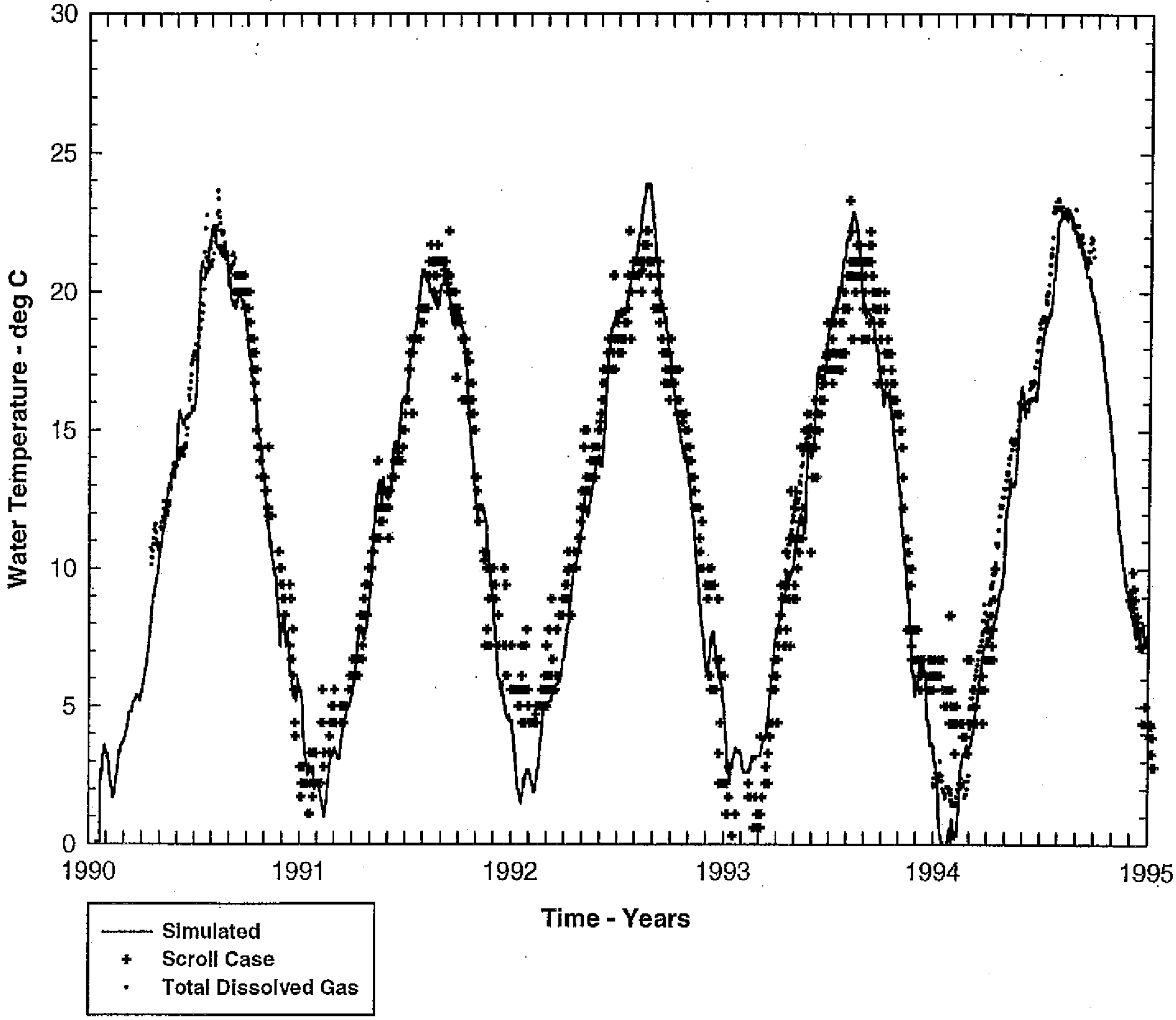


Figure 10. Simulated and observed water temperatures at Bonneville Dam for the period 1990-1994.

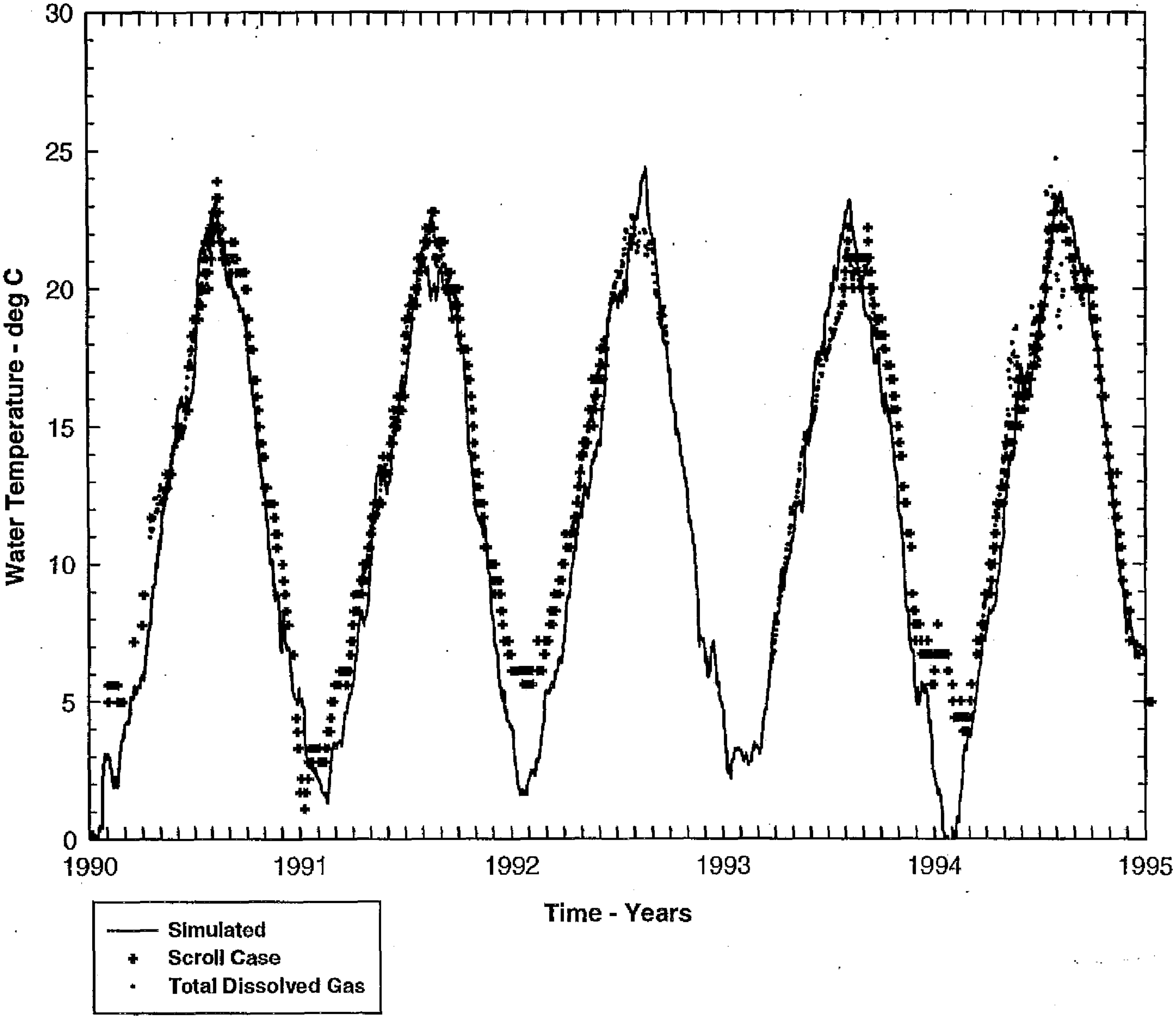


Figure 11. Simulated and observed water temperatures at Lower Granite Dam for the period 1990-1994.

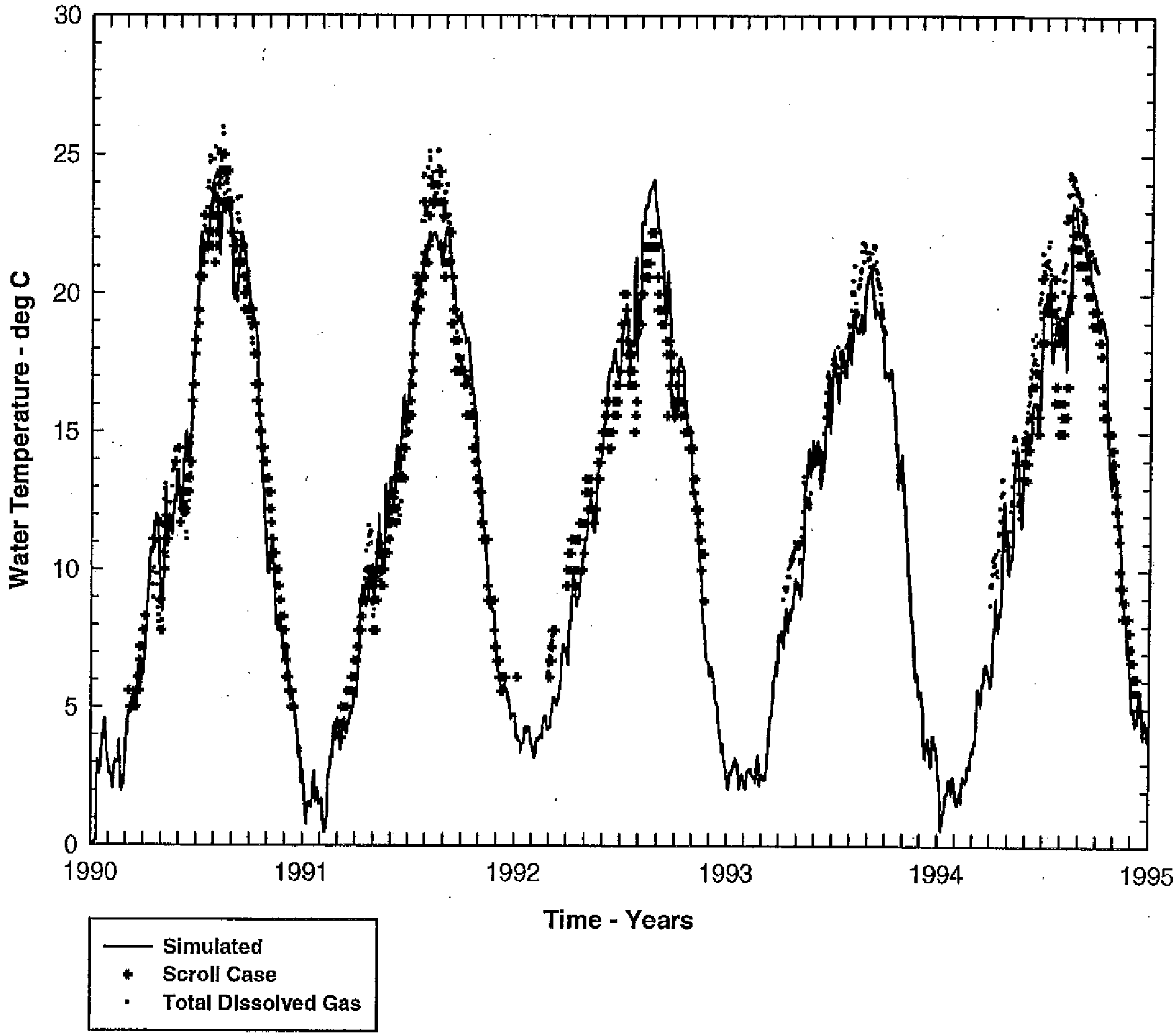


Figure 12. Simulated and observed water temperatures at Little Goose Dam for the period 1990-1994.

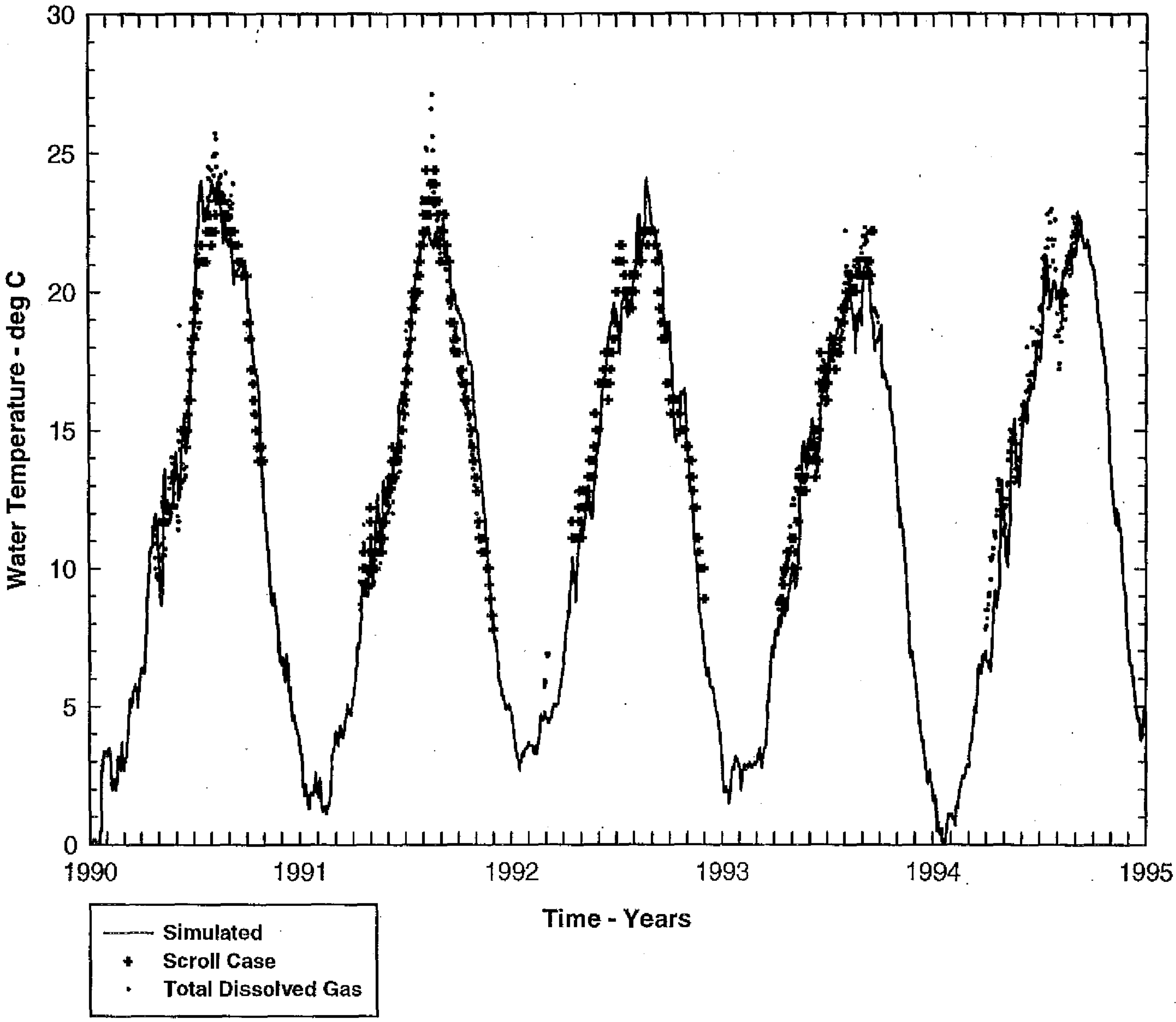


Figure 13. Simulated and observed water temperatures at Lower Monumental Dam for the period 1990-1994.

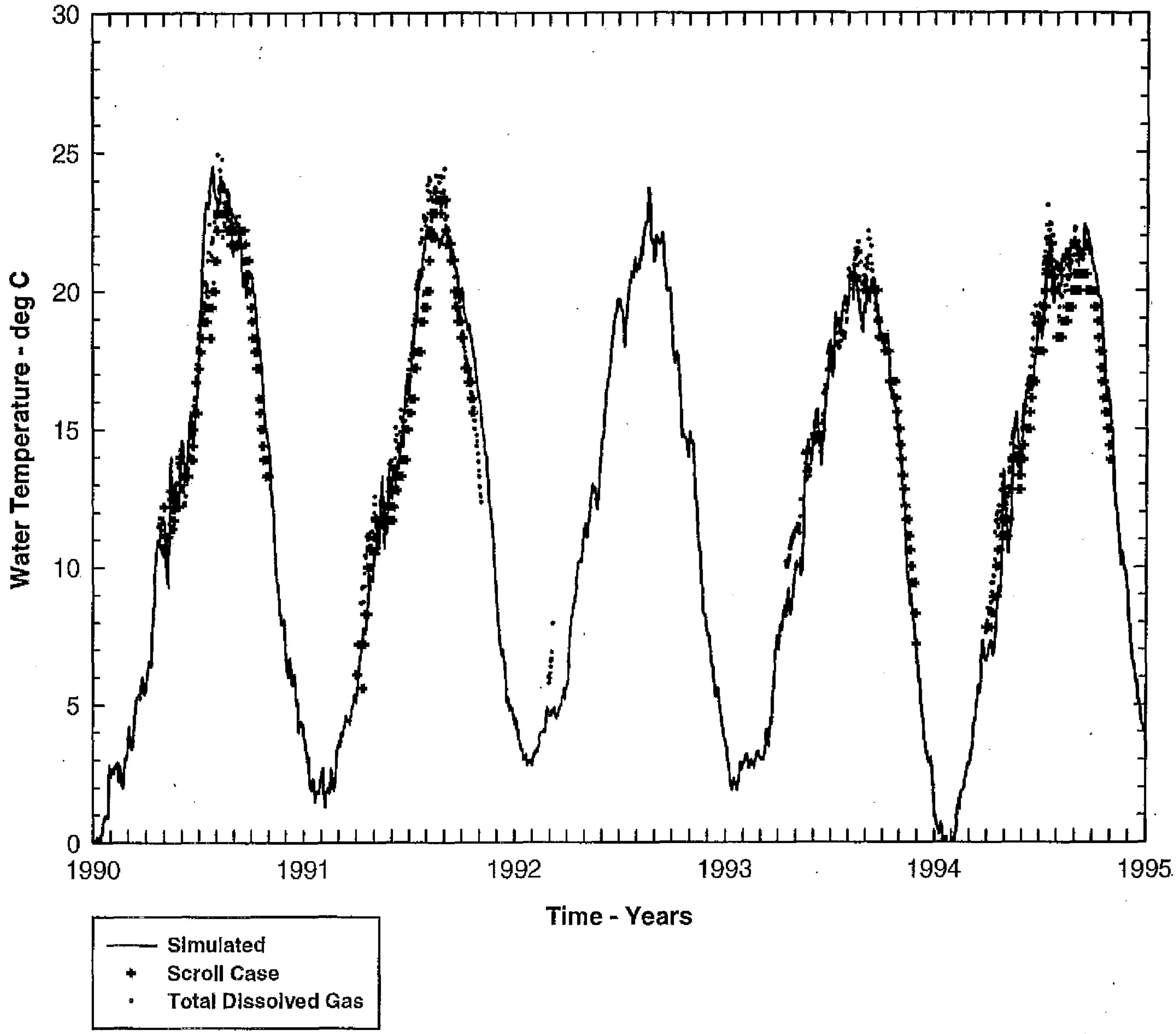
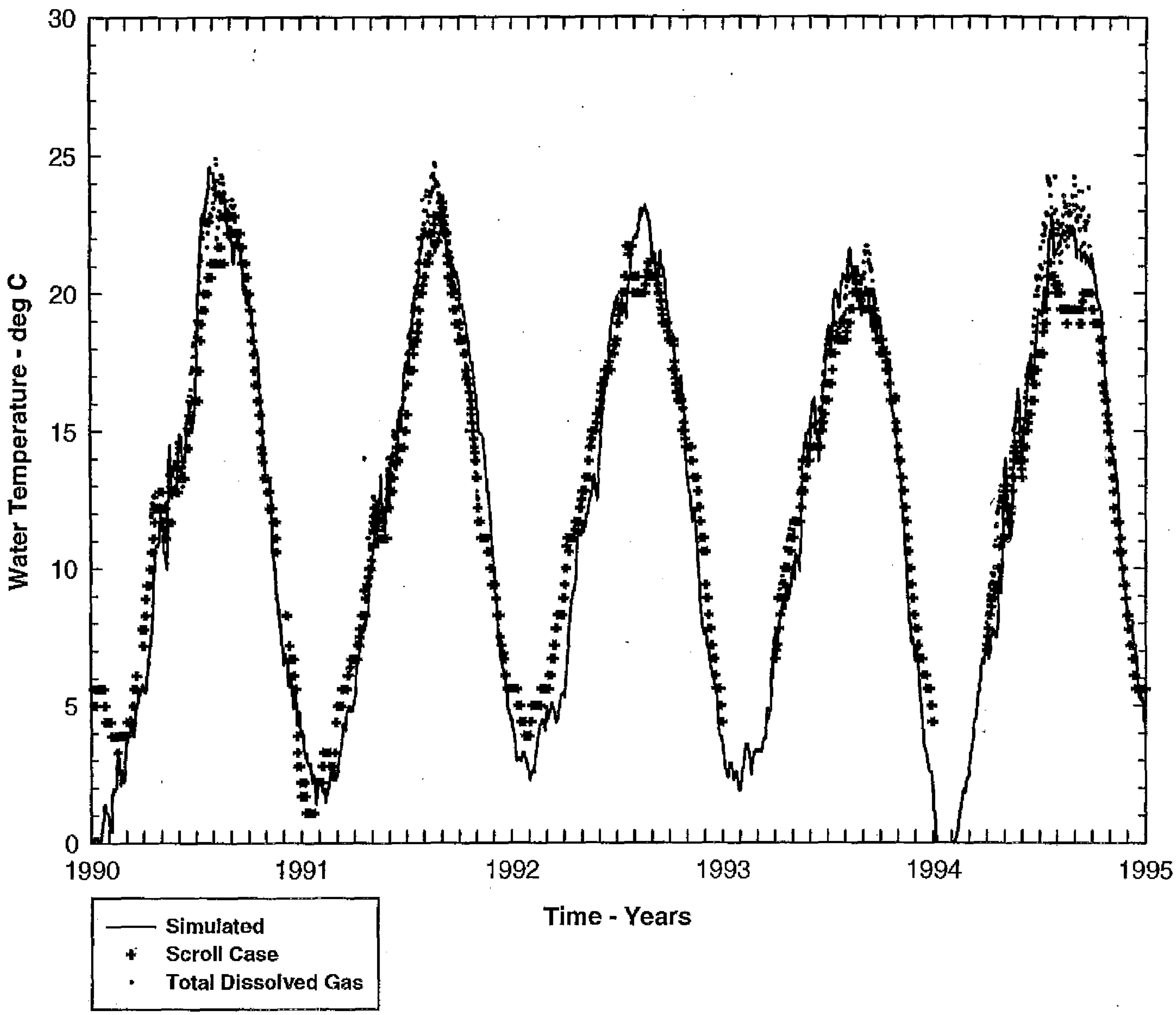


Figure 14. Simulated and observed water temperatures at Ice Harbor Dam for the period 1990-1994.



Appendix D: Statistical Analysis of RBM10 Simulations From Yearsley, 1999).

APPENDIX D

Statistical Analysis
Of
Simulation Results

The statistical analyses were performed in this study to quantify levels of uncertainty associated with simulation results. Means and standard deviations of the difference between observed and simulated temperatures were computed for the entire simulation period and for each two-month period for the duration of the simulation (01/01/1990 – 12/31/1994). The results are given in Tables D-1 through D-9. An analysis of the regression of observed results on simulated results was also performed. In the regression analysis, the linear relationship is constrained to pass through the origin of the coordinates at (X=0, Y=0) as shown in Figures D-1 through D-9. The results of the regression are shown Table D-10.

Certain statistics are also generated as part of the parameter estimation process. These include the theoretical and sample variance of the innovations process Figures D-10 through D-18 and.the innovations process (Equation 12) (Figures D-19 through D-27).

When reviewing these statistics it is important to keep in mind that the means and standard deviations of the difference between observed and simulated are based on state estimates using the model in the *prediction* mode. That is, the state estimates from the model do not depend on prior observations. The statistics generated by the parameter estimation process are a result of using the model in the *filtering* mode. This means that the innovations sequence, the difference between observed and the systems update prior to filtering, is a function of previous observations and state estimates. In addition, the parameter estimation process attempts to estimates the bias in the observations.

Table D-1. Mean and standard deviation of the difference between observed and simulated temperatures at Wells Dam (Columbia River Mile 515.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	-0.028	0.510
May-June	0.035	0.802
July-August	-0.136	0.529
September-October	0.494	0.488
November-December	---	--
Entire Year	0.009	0.677

Table D-2. Mean and standard deviation of the difference between observed and simulated temperatures at Priest Rapids Dam (Columbia River Mile 397.1) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.320	0.999
May-June	-0.623	0.895
July-August	-0.499	0.880
September-October	0.855	0.433
November-December	---	--
Entire Year	-0.277	1.012

Table D-3. Mean and standard deviation of the difference between observed and simulated temperatures at McNary Dam (Columbia River Mile 292.0) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.940	0.929
May-June	0.749	1.194
July-August	0.884	1.335
September-October	1.653	1.027
November-December	---	--
Entire Year	0.983	1.236

Table D-4. Mean and standard deviation of the difference between observed and simulated temperatures at John Day Dam (Columbia River Mile 215.6) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	0.580	1.309
March-April	1.273	0.730
May-June	0.283	0.924
July-August	0.288	0.986
September-October	0.9425	0.646
November-December	---	---
Entire Year	0.560	1.021

Table D-5. Mean and standard deviation of the difference between observed and simulated temperatures at Bonneville Dam (Columbia River Mile 215.6) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.909	1.002
May-June	0.413	1.248
July-August	-0.382	1.423
September-October	0.524	0.868
November-December	---	---
Entire Year	0.241	1.306

Table D-6. Mean and standard deviation of the difference between observed and simulated temperatures at Bonneville Dam (Columbia River Mile 215.6) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	0.909	1.002
May-June	0.413	1.248
July-August	-0.382	1.423
September-October	0.524	0.868
November-December	---	---
Entire Year	0.241	1.306

Table D-7. Mean and standard deviation of the difference between observed and simulated temperatures at Lower Granite Dam (Snake River Mile 107.5) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.052	1.388
May-June	-0.040	1.363
July-August	1.136	1.120
September-October	0.409	1.076
November-December	-0.133	0.203
Entire Year	0.588	1.320

Table D-7. Mean and standard deviation of the difference between observed and simulated temperatures at Little Goose Dam (Snake River Mile 70.3) for the period 1990-1994. Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.086	1.144
May-June	-0.196	1.167
July-August	0.131	1.532
September-October	-0.228	1.436
November-December	---	---
Entire Year		

Table D-8. Mean and standard deviation of the difference between observed and simulated temperatures at Lower Monumental Dam (Snake River Mile 41.6) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.543	0.900
May-June	0.027	0.884
July-August	-0.067	1.269
September-October	-0.036	0.933
November-December	---	---
Entire Year		

Table D-9. Mean and standard deviation of the difference between observed and simulated temperatures at Ice Harbor Dam (Columbia River Mile 9.7) for the period 1990-1994. . Observed data are from the total dissolved gas monitoring locations in the forebay of the dam at a depth of 15 feet. Dashes (---) indicate limited (N<10) data for computing statistics

Time Period	Mean Difference	Standard Deviation of Difference
January-February	---	---
March-April	1.784	1.021
May-June	0.155	0.888
July-August	0.192	1.190
September-October	0.625	1.093
November-December	---	---
Entire Year	0.407	1.202

Table D-10. Slope of line and R^2 for regression of observed temperature data on simulated results in the Columbia and Snake rivers for the period 1990-1994. Regression was constrained to force the straight line to pass through the origin (X (simulated)=0, Y (observed)=0).

Measurement Site	Slope of Line	R^2
Wells Dam	0.995	0.973
Priest Rapids Dam	0.999	0.940
McNary Dam	1.004	0.929
John Day Dam	0.995	0.976
Bonnevile Dam	0.995	0.904
Lower Granite Dam	1.005	0.931
Little Goose Dam	0.997	0.907
Lower Monumental Dam	0.992	0.923
Ice Harbor Dam	0.998	0.929